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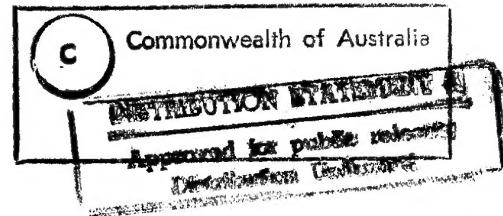


Theoretical Estimates of High Frequency  
Acoustic Attenuation and Backscattering  
from Suspended Sand Particles in the  
Ocean and in an Estuary

R.A. Thuraisingham

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# Theoretical Estimates of High Frequency Acoustic Attenuation and Backscattering from Suspended Sand Particles in the Ocean and in an Estuary

*R.A. Thuraisingham*

Maritime Operations Division  
Aeronautical and Maritime Research Laboratory

DSTO-TR-0078

## ABSTRACT

Theoretical estimates of high frequency sound attenuation and backscattering strengths from suspended sand particles in the ocean and in an estuary are given. The estimates are obtained using the measured volume concentrations of suspended particle in the upper layers of the ocean [Duykers, 1967], from the particle size spectra near the clear water minimum [McCave, 1984], and from measurements of suspended sediments at different depths from the bottom of an estuary, [Thorne, et al, 1993]. Estimates are given for frequencies in the 1-10 MHz region. Contributions to acoustic attenuation from scattering, viscous drag and thermal conduction are evaluated separately using existing theoretical models. Contribution to attenuation from thermal conduction is negligible at the frequencies used. For particles in the sub micrometer to 10  $\mu\text{m}$  range attenuation is predominantly due to viscous drag. For large particles scattering is the main cause of attenuation. Estimates reveal attenuation and backscattering near the bottom of the estuary is quite high. At 5 MHz, attenuation at a depth of 80 cm and 10 cm from the bottom are approximately 0.1 dB/m and 10 dB/m respectively. At this frequency backscattering strength at 80 cm and 10 cm depths from the bottom, are approximately -25 dB and -5 dB respectively.

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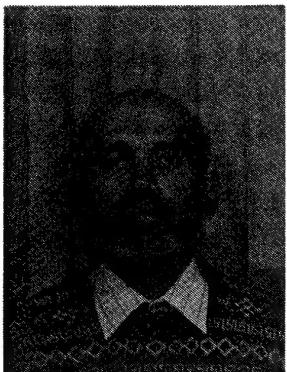
# Theoretical Estimates of High Frequency Acoustic Attenuation and Backscattering from Suspended Sand Particles in the Ocean and in an Estuary

## EXECUTIVE SUMMARY

This study looks at attenuation and backscattering of MHz sound by suspended sand particles. It is part of a project to investigate the use of sound in the MHz region, to image objects in sea. The study examines the relative importance of various mechanisms that causes attenuation of sound by suspended sand particles and gives theoretical estimates of attenuation and backscattering at MHz frequencies. Estimates are given from regions ranging from clear water to those close to the bottom of an estuary. The study shows that for particles that have a radius less than 10 microns viscous drag is the predominant mechanism for attenuation, while for large particles it is scattering. Estimates indicate that attenuation and backscattering close to the bottom of the sea will be high, which can cause problems for acoustic visibility.

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## List of Symbols

$f$	<i>frequency</i>
$\omega$	<i>radian frequency</i>
$c$	<i>velocity of sound in surrounding medium</i>
$c_1, c_2$	<i>velocity of compressional and shear sound waves in the particle</i>
$k$	<i>wave number in surrounding medium</i>
$\rho, \rho_1$	<i>density of medium and particle</i>
$a$	<i>radius of particle</i>
$ f(\bar{o}, \bar{i}) ^2$	<i>angular scattered intensity function</i>
$\bar{o}, \bar{i}$	<i>scattered and incident directions</i>
$j_m$	<i>spherical Bessel functions of the first kind of order <math>m</math></i>
$y_m$	<i>spherical Bessel functions of the second kind of order <math>m</math></i>
$\Sigma_s$	<i>total scattering cross section of a particle</i>
$\nu$	<i>kinematic viscosity of the fluid</i>
$N$	<i>number of particles per <math>m^3</math></i>
$\tau$	<i>thermal conductivity</i>
$\sigma$	<i>thermometric conductivity</i>
$C_p$	<i>specific heat at constant pressure</i>
$I_{bs}$	<i>intensity of backscattered sound 1 m from a unit volume of scatterers</i>
$I_i$	<i>incident intensity of sound</i>
$BS$	<i>scattering strength</i>

## 1. Introduction

The importance of high frequency sound attenuation and backscattering from suspended particulate material in the ocean is assessed in this report, using theoretical models. The study is undertaken to evaluate the feasibility of using high frequency sound in the MHz region to obtain an image of an object in sea. One of the problems associated with the use of visible light is the large scattering caused by suspended particles.

Most of the early work in the distribution of total suspended material (TSM) came from light scattering measurements. Jerlov [1953] employing light scattering measurements undertook one of the first major surveys of the oceanic TSM. From the data he was able to identify a number of overall trends in the distribution of TSM, including the recognition of what were subsequently termed nepheloid layers, that is layers of relatively turbid waters that can extend hundreds of metres above the sea bed. This was followed by a series of investigations by Russian scientists in the 1950's, [Lisitzin, 1972], and by American groups in the 1960's, [Ewing and Thorndike, 1965; Connary and Ewing, 1972, p169-184]. Recent studies of the global distribution of the oceanic TSM have been carried as part of the GEOSECS and HEBBLE programs, using sediment traps in many locations. From these data the distribution of oceanic TSM can be described in terms of a three layer model in which the main features are, a surface layer, a clear water minimum layer and a deep water layer. A detailed description of the distribution of TSM is given in Chester [1990, p321-345].

Attenuation of sound by suspended material can be due to scattering, viscous drag or thermal conduction. Sections 2-4 describe theoretical evaluations of these three mechanisms, respectively. Section 5 describes the method to evaluate back scattering strength. In section 6 numerical estimates of attenuation and backscattering strength are given for 4 cases. The first case uses the volume concentration of particles inferred for the upper layers (0-200 m) of the ocean by Duykers [1967], using low frequency acoustic data. The second case uses the particle size distribution of McCave [1984], which was measured near the clear water minimum. The third case involved the use of the measured particle size distribution in the Bay of Bengal, in the Indian ocean [Shifrin, 1988, p266]. Finally estimates are obtained from suspended sediment measurements in an estuary, at different distances from the bottom [Thorne, et al, 1993]. In the evaluation of estimates particulate matter is assumed to be sand, that is silica. Suspended organic matter, such as phytoplankton, and zooplankton are poor scatterers and absorbers when compared to sand. Estimates are given for frequencies in the 1-10 MHz region, because of a current interest in mine imaging, for classification.

## 2. Attenuation Due to Scattering

Preliminary studies on the use of available models to estimate scattering of sound due to sand particles, for high frequency sound, gave the following results: Application of the Rayleigh approximation, which is applicable when the particle size is much less than the wavelength of sound, for particles having radius larger than 44  $\mu\text{m}$  at frequencies above 3 MHz can lead to significant errors. Results from the non-rigid sphere model [Morse and Ingard, 1968, p337], are always less than the rigid sphere model [Morse and Ingard, 1968, p419] by a factor of 2 or 3, while the inclusion of shear waves has effects for large particles (radius > 150  $\mu\text{m}$ ). Due to the presence of such large particles near the sea bottom and in a turbid medium, the most suitable approach would be to consider the suspended material to be non-rigid spheres and to include shear waves.

The angular scattered intensity function  $|f(\vec{o}, \vec{i})|^2$ , which gives the angular distribution of the scattered intensity, for a non rigid sphere with the inclusion of shear waves is given by [Faran, 1951; Hickling, 1962],

$$|f(\vec{o}, \vec{i})|^2 = \frac{1}{k^2} \sum_{l,m=0}^{\infty} (2m+1)(2l+1) \sin \eta_m \sin \eta_l \cos(\eta_m - \eta_l) P_l(\cos \theta) P_m(\cos \theta) \quad (1)$$

where  $\theta$  is the angle between  $\vec{o}$  and  $\vec{i}$ , the scattered and incident directions and  $P_l, P_m$  the Legendre polynomials of order  $l$  and  $m$  respectively.  $k$  is the wave number of the incident wave ( $= \frac{2\pi f}{c}$ ),  $f$  the frequency, and  $c$  is the sound speed in the surrounding medium. Other parameters necessary to evaluate the angular scattered intensities are given below.

$$\tan \eta_m = \frac{\tan \delta_m(x)(\tan \phi_m + \tan \alpha_m(x))}{\tan \phi_m + \tan \beta_m(x)}$$

$$\tan \delta_m(x) = \frac{-j_m(x)}{y_m(x)}$$

$$\tan \alpha_m(x) = \frac{x j_{m+1}(x)}{j_m(x)} - m$$

$$\tan \beta_m(x) = \frac{x y_{m+1}(x)}{y_m(x)} - m$$

$$\tan \zeta_m(x_1, x_2) = -0.5 x_2^2 \left( \frac{z_1 - z_2}{z_3 - z_4} \right)$$

$$z_1 = \frac{\tan \alpha_m(x_1)}{\tan \alpha_m(x_1) + 1}$$

$$z_2 = \frac{m^2 + m}{m^2 + m - 1 - 0.5 x_2^2 + \tan \alpha_m(x_2)}$$

$$z_3 = \frac{m^2 + m - 0.5 x_2^2 + 2 \tan \alpha_m(x_1)}{\tan \alpha_m(x_1) + 1}$$

$$z_4 = (\tan \alpha_m(x_2) + 1)z_2$$

$$\tan \phi_m = \frac{-\rho}{\rho_1} \tan \zeta_m(x_1, x_2)$$

where  $x = ka$ ,  $x_1 = k_1 a$ ,  $x_2 = k_2 a$ .

Wave numbers  $k_1$  and  $k_2$  are  $\frac{2\pi f}{c_1}$  and  $\frac{2\pi f}{c_2}$ , respectively, where  $c_1$ ,  $c_2$  are the

velocity of compression and shear sound waves in the particle of radius  $a$ .  $\rho$ ,  $\rho_1$  are the densities of the medium and particle respectively.  $j_m$  are spherical Bessel functions of the first kind of order  $m$  and  $y_m$  are spherical Bessel functions of the second kind of order  $m$ . The functions  $y_m$  are also referred to as spherical Neumann functions of order  $m$ , [Morse and Ingard, 1968, p337].

The total scattering cross section of a particle is given by:

$$\sum_i = 2\pi \int_0^\pi |f(\bar{o}, \vec{i})|^2 \sin \theta d\theta$$

This is the total scattered radiation by a single particle per unit volume. For a non rigid sphere with the inclusion of shear waves, using eqn(1) gives:

$$\sum_i = \frac{4\pi}{k^2} \sum_{m=0}^{\infty} (2m+1) \sin^2 \eta_m \quad (2)$$

Suppose the particle number density (the number of particles per  $m^3$ ) is  $N$ , then the total scattering loss in dB/m is given by

$$4.342N\sum_i \quad (3)$$

The evaluation of the spherical Bessel functions  $j_m$ , of all orders is carried out using the procedure due to Miller, [Abramowitz and Stegun, 1970, p452]. The spherical Bessel functions  $y_m$  are obtained by first evaluating  $j_m$  for negative  $m$  using  $j_{m-1}(x) + j_{m+1}(x) = (2m+1)x^{-1}j_m(x)$  recursively, and then calculating  $y_m$  from the relationship  $y_m(x) = (-1)^{m+1} j_{-m-1}(x)$ , [Abramowitz and Stegun, 1970, p439].

### 3. Viscous Attenuation

This section examines the effect due to viscosity on sound attenuation. Lamb [1945] derived the theory to obtain attenuation of sound energy by particles due to the viscosity of the medium. The particles were considered to be rigid and incompressible but free to move. This was tested by Urick [1948] who obtained good agreement with the theory of Lamb in his measurements on sand and kaolin particles at megacycle frequencies. Later Hovem [1980] also found good agreement in suspensions provided the volume concentration of the suspended material is no more than a few percent. In the ocean volume concentrations of suspended particles are less than a percent. The theory of Lamb is therefore suitable to study viscous attenuation in the ocean.

Lamb [1945] calculated the attenuation due to viscosity by finding the velocity potential of the waves scattered by the particle and then obtaining the average rate at which work is being done over the spherical surface surrounding the particle. For  $ka < 1$ ,  $k$  being the wave number of incident acoustic wave, he showed that attenuation due to viscosity becomes important when the radius of the particle is less than or comparable to  $\beta^{-1} = (\frac{2v}{\omega})^{\frac{1}{2}}$ , where  $v$  is the kinematic viscosity of the fluid and  $\omega (= 2\pi f)$  is the radian frequency. For  $a \ll \beta^{-1}$  or  $a \gg \beta^{-1}$  viscous effects are minimal, [Urick and Ament, 1949]. The attenuation due to viscosity in dB/m for particles of radius  $a$  is given by, [Lamb, 1945, p660]

$$4.342N \frac{4\pi}{k^2} \operatorname{Real}(iA_1B_1 - iA_0B_0)$$

where  $N$  is the number of particles per  $m^3$ ,

$$\begin{aligned} A_1 &= \frac{-(3+3iha-(ha)^2)(ka)^3 e^{ika}}{(ka)^2(1+iha)+(2+2ika-(ka)^2)(ha)^2} \\ B_1 &= \frac{\rho_1 - 3\rho_0 \psi(ka)}{\rho_1 - \rho_0 - \rho_0(ka)f_1(ka)A_1} \\ \psi(ka) &= \frac{\sin(ka)}{(ka)^3} - \frac{\cos(ka)}{(ka)^2} \\ f_1(ka) &= e^{-ika} \left( \frac{-3i}{(ka)^3} - \frac{3}{(ka)^4} + \frac{1}{(ka)^2} \right) \end{aligned} \quad (4)$$

$$ha = (1-i)\beta a.$$

$A_0$  and  $B_0$  are the values of  $A_1$  and  $B_1$  when  $ha \rightarrow \infty$ . The above expression is not limited to extremely small values of  $ka$ .

A much simpler formula used by Urick [1948] and also by Ahuja[1970] for rigid particles of radius 'a' and valid for  $ka \ll 1$  is,

$$4.342 N \left( \frac{4}{3} \pi a^3 \right) k \left( \frac{\rho_1}{\rho} - 1 \right) \frac{s}{s^2 + \left( \frac{\rho_1}{\rho} + t \right)^2}$$

$$s = \frac{9}{4\beta a} \left( 1 + \frac{1}{\beta a} \right)$$

$$t = 0.5 + \frac{9}{4\beta a}$$

## 4. Thermal Attenuation

In this section the effect of thermal conduction on sound attenuation is examined. Epstein and Carhart [1953], in their investigation of sound absorption by fog particles, obtained a result to estimate attenuation of sound due to thermal conduction. Allegra and Hawley [1971] found good agreement with their attenuation results in emulsions where thermal transport processes are important. Provided  $\frac{4\pi f \sigma}{c^3} \ll 1$ , where  $\sigma$  is the thermometric conductivity of the medium, defined by  $\frac{\tau}{\rho C_p}$ ,  $\tau$  being the thermal conductivity and  $C_p$  the specific heat at constant pressure, an estimate of attenuation due to thermal conduction can be obtained. For frequencies of interest here (1-10 MHz), and for sea water this ratio is  $\ll 1$ . The thermal attenuation in dB/m due particles of radius  $a$  is then given by Epstein and Carhart [1953] as

$$4.342(4\pi N(\gamma - 1)\left(\frac{\sigma}{c}\right)a(1-\xi)^2 \operatorname{Real}\left(\frac{1}{F}\right)), \quad (5)$$

where

$$\gamma = \frac{C_p}{C_v},$$

$$\xi = \chi\left(\frac{\alpha_1 \sigma_1}{\alpha \sigma}\right)$$

$$\text{and } F = \left(\frac{1}{1-ib}\right) - \chi \frac{\sin b_1}{\sin b_1 - b_1 \cos b_1}$$

The parameter  $b$  is defined by,  $b = (1+i)\left(\frac{2\pi f}{2\sigma}\right)^{\frac{1}{2}} a$ . The suffix 1 indicates particle.

$\chi = \frac{\tau}{\tau_1}$ , and  $\alpha$  is the coefficient of volume expansion. The expression is valid for  $ka \ll 1$ . For other values of  $ka$  attenuation from thermal conduction is negligible. The necessary thermal data for sand and sea water are obtained from Kaye and Laby [1972], and Walton Smith [1974].

## 5. Backscattering Strength

Backscattering strength(BS) in dB is defined as,

$$BS = 10 \log_{10} \left( \frac{I_{bs}}{I_i} \right),$$

where  $I_{bs}$  is the intensity of the backscattered sound at a distance of 1m from a unit volume of scatterers and  $I_i$  is the incident intensity. If scattering is omnidirectional then

$$BS = 10 \log\left(\frac{N\Sigma_t}{4\pi}\right). \quad (6)$$

This would be the case if  $ka \ll 1$ . Otherwise

$$BS = 10 \log_{10}(N|f(180^\circ)|^2) \quad (7)$$

where  $|f(180^\circ)|^2$  is the angular scattered intensity function given by eqn(1), evaluated for  $\theta = 180^\circ$ . The angular scattered intensity function is the same as the commonly described volume scattering function.

## 6. Numerical Estimates

In this section numerical estimates for attenuation, and backscattering strength due to suspended sand particles are presented from experimentally measured particle concentrations or distributions. Figure 1(a) shows the total attenuation and contributions due to scattering, viscous drag and thermal conduction, for seawater containing particles with a uniform radius, as a function of particle radius at 5 MHz. The volume concentration of particles is taken as  $6 \times 10^{-6}$ , this being inferred by Duykers [1967] from acoustic measurements in the upper layers (0 -200m) of the ocean. The particle radius was varied from  $0.5 \mu m$  to  $50 \mu m$ . Attenuation due to thermal conduction is negligible at all particle sizes. For particles with radii less than  $10 \mu m$  viscous drag is the dominant effect of attenuation, while beyond  $10 \mu m$  scattering contributes the most to attenuation, [Uric,1948]. The variation of viscous attenuation with radius is explained as follows.

When sound wave passes through the medium, the particles will oscillate with the fluid. If the medium is viscous then there will be loss of energy due to drag. The drag force that causes dissipation depends on the relative speed between particle and fluid and on the surface area of the particle. Small particles have a low inertia and vibrate to and fro along with the fluid. Hence the relative speed is small. On the other hand large particles have a high inertia and tend to lag behind. However for a constant volume concentration of particles, the available surface area will decrease with increase in radius. The combination of these two effects results in viscous attenuation at a particular frequency being important only for smaller radii. This is seen in Fig. 1(a). Fig. 1(b) shows the backscattering strength at 5 MHz as a function of the particle radius. The backscattering increases with particle radius.

From measurements of particle size spectra near the clear water minimum, McCave [1984] showed that the particle number data can nearly always be fitted by a power law distribution over a large part of the measured range. Expressed as a cumulative number  $N_0$  as a function of particle diameter  $d$ , the size distribution is described by

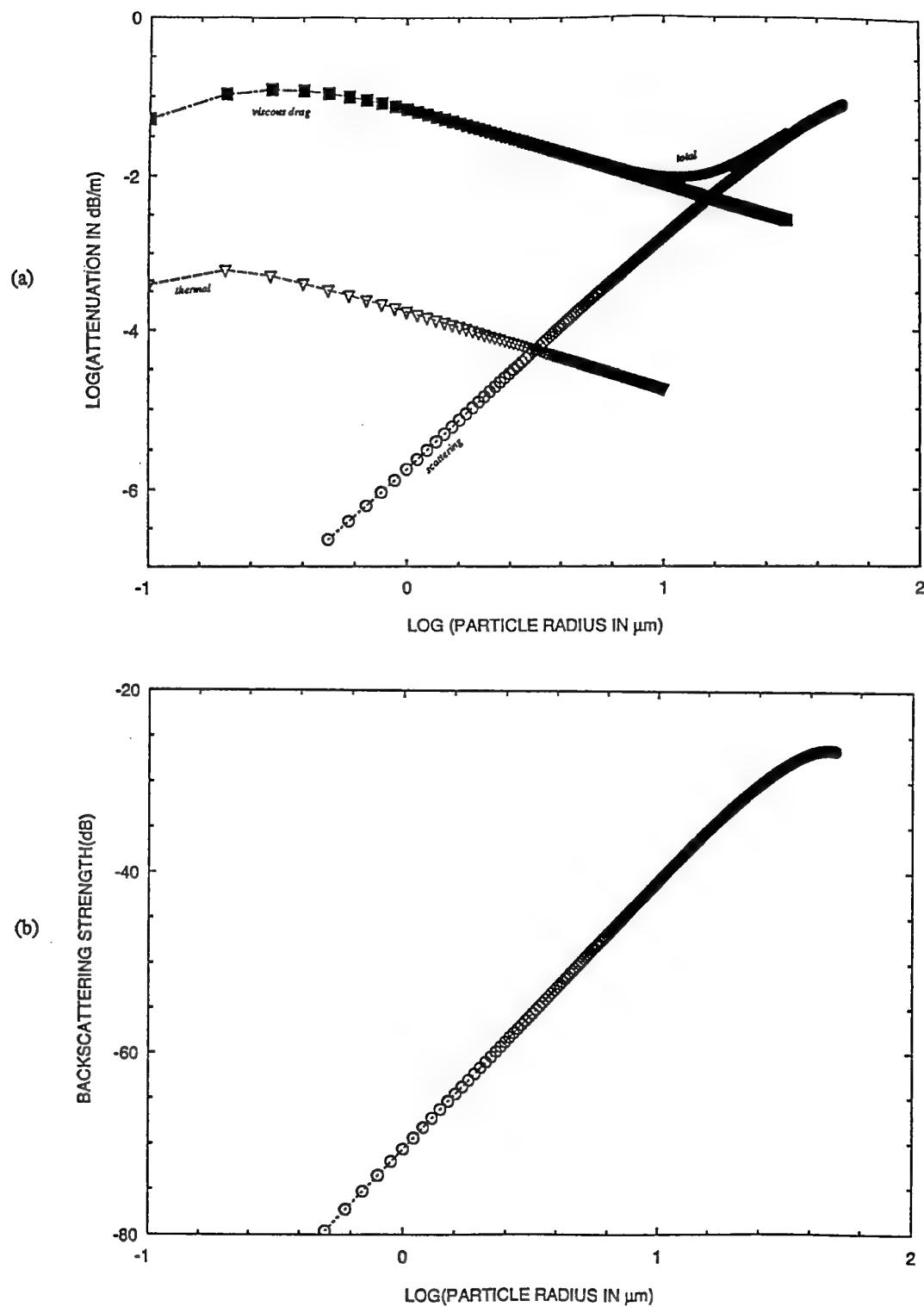
$$N_0 = k_c d^{-3}$$

for  $d$  in the range  $1-100 \mu m$ , and  $k_c = 5 \times 10^9$  per  $m^3$ .  $N_0$  is the number of particles with diameter  $> d$ . This indicates equal particle volumes in logarithmically increasing size grades. Fig. 2(a) gives the attenuation due to viscous drag, scattering and the total, for frequencies 1-10 MHz for such a distribution. The attenuation values are small.

Fig.2(b) shows the backscattering strength for frequencies 1-10 MHz for such a distribution. Backscattering strength increases with frequency.

Shifrin [1988, p266] has presented data on the distribution of particles obtained from measurements made in the summer of 1979 in the Indian Ocean. One of them is the result from the Bay of Bengal in the vicinity of the Ganges. The particle distribution given is obtained at depth of 10m. Most of the particles have radii less than  $1 \mu m$ . Figure 3(a) gives the attenuation due to viscous drag, scattering and total, for frequencies 1-10 MHz. Attenuation due to thermal conduction is negligible. Most of the attenuation is due to viscous drag, which arises due to the presence of a large number of particles that have radii less than  $1 \mu m$ . Figure 3(b) shows the backscattering strength for frequencies 1-10 MHz. It increases with frequency but the values are similar to that of clear water due to the absence of large particles that contribute to scattering.

Thorne et al [1993], carried out suspended sediment measurements in an estuary at different depths close to the bottom. The bed consists of well-sorted fine sand with little clay or silt present in the bed or in the water column. Analysis of the samples at 10 and 80 cm above the bed showed a Gaussian probability distribution with an average radius of  $85 \mu m$  and  $78 \mu m$  respectively and a standard deviation of  $20 \mu m$ . The total concentrations of particles at these two depths are  $1 kg / m^3$  and  $10^{-2} kg / m^3$ . Fig. 4(a) shows the attenuation due to viscous drag and scattering 80 cm from the bottom for frequencies in the 1-10 MHz region, while Fig. 4(b) is for measurements 10 cm from the bottom. Due to the large sediment particle size present viscous attenuation is small compared to scattering. Figures 5(a) and 5(b) are the backscattering strength as a function of frequency for the 2 depths 80 cm and 10 cm from the bottom. The plateau observed in the backscattered strength is due to the modes of vibration of the elastic sphere being excited at certain frequencies which then interfere destructively with the backscattered signal, [Thorne et al ,1992]. It is a resonance phenomenon. It is absent if the particles are considered rigid. We are able to observe this in the estuarine measurements due to the presence of large particles, but it is absent in the region of the clear water minimum.



*Figure 1: (a) Total attenuation and attenuation due to scattering, viscous drag and thermal conduction, in dB/m and (b) Backscattering strength, as a function of particle radius at 5 MHz. Volume concentration of particles  $6 \times 10^{-6} \text{ cm}^3$ .*

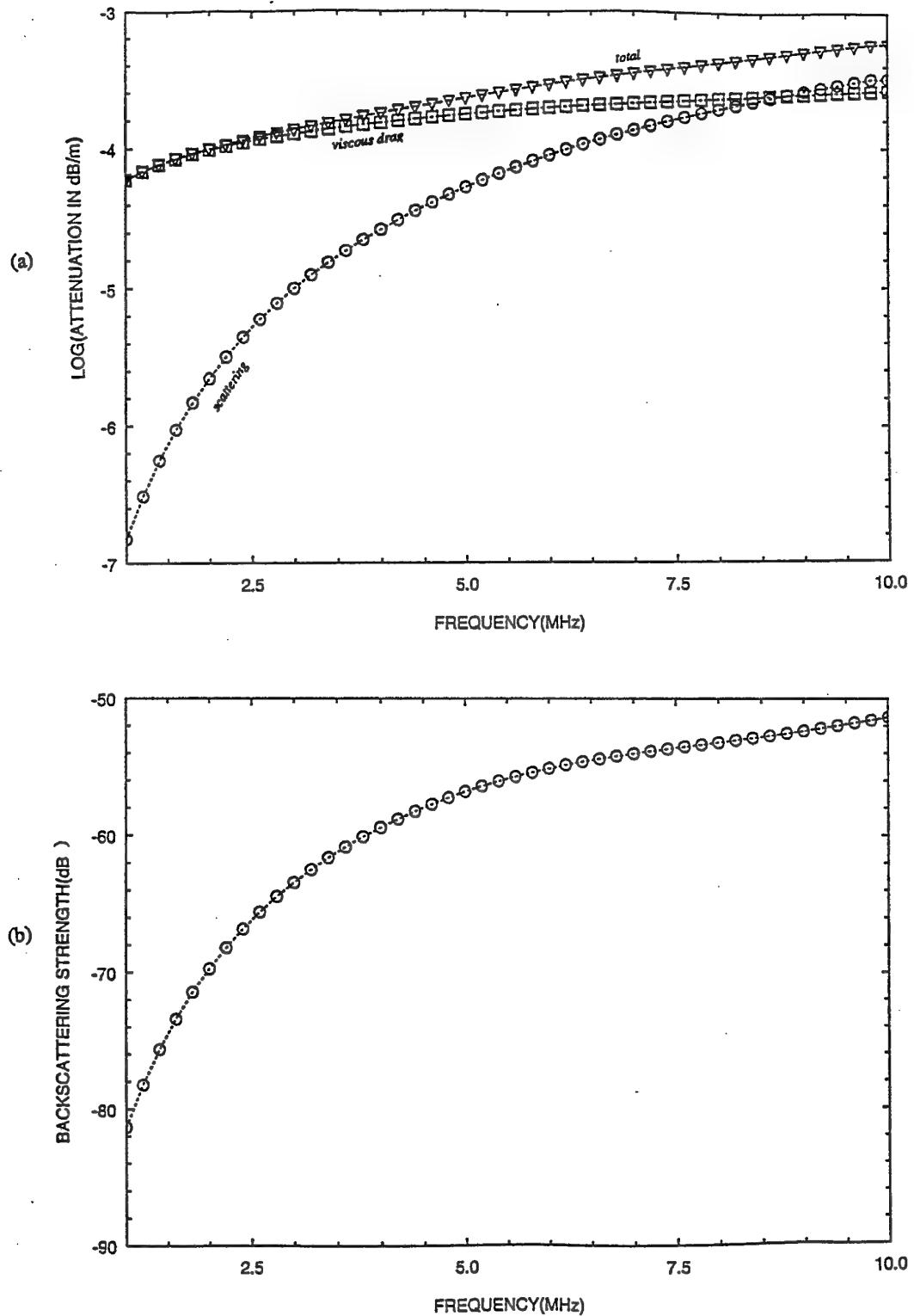
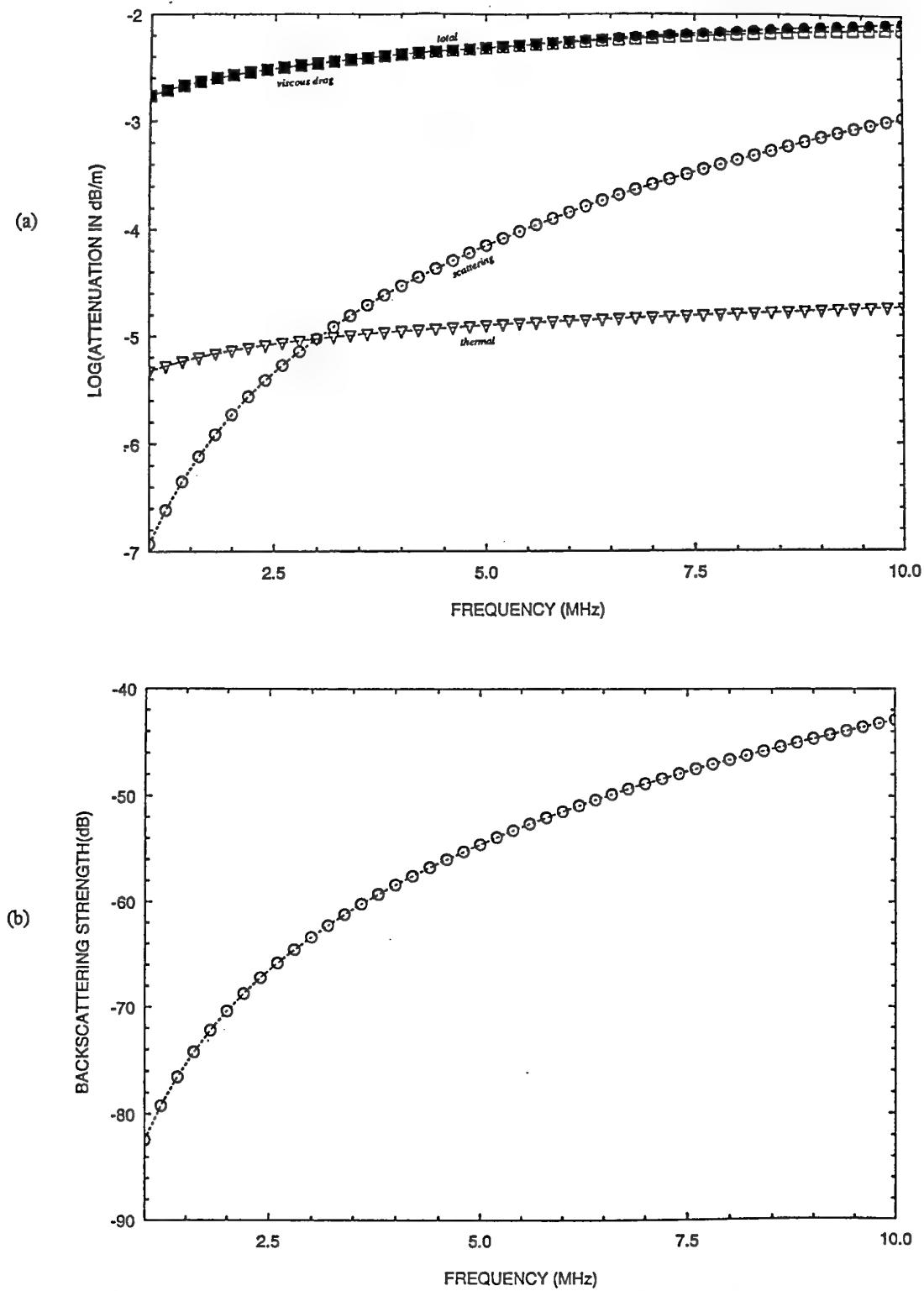


Figure 2: (a) Total attenuation and attenuation due to scattering and viscous drag in dB/m, and (b) Backscattering strength, in the clear water minimum as a function of frequency.



*Figure 3: (a) Total attenuation and attenuation due to scattering, viscous drag and thermal conduction, in dB/m and (b) Backscattering strength, in the Bay of Bengal in the Indian ocean, as a function of frequency.*

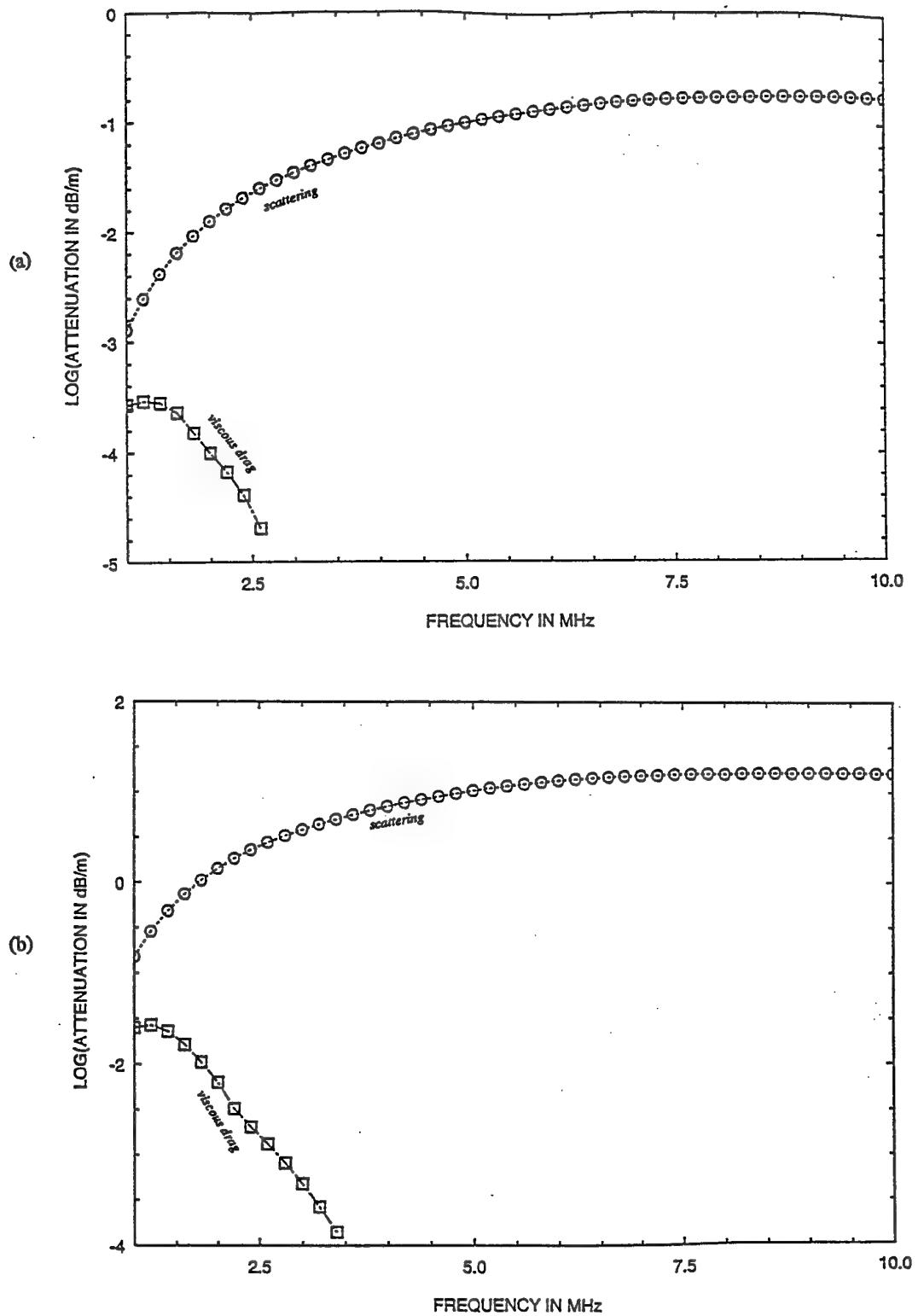


Figure 4: Attenuation in dB/m, due to scattering and viscous drag at (a) 80 cm and (b) 10 cm from the bottom for frequencies 1-10 MHz.

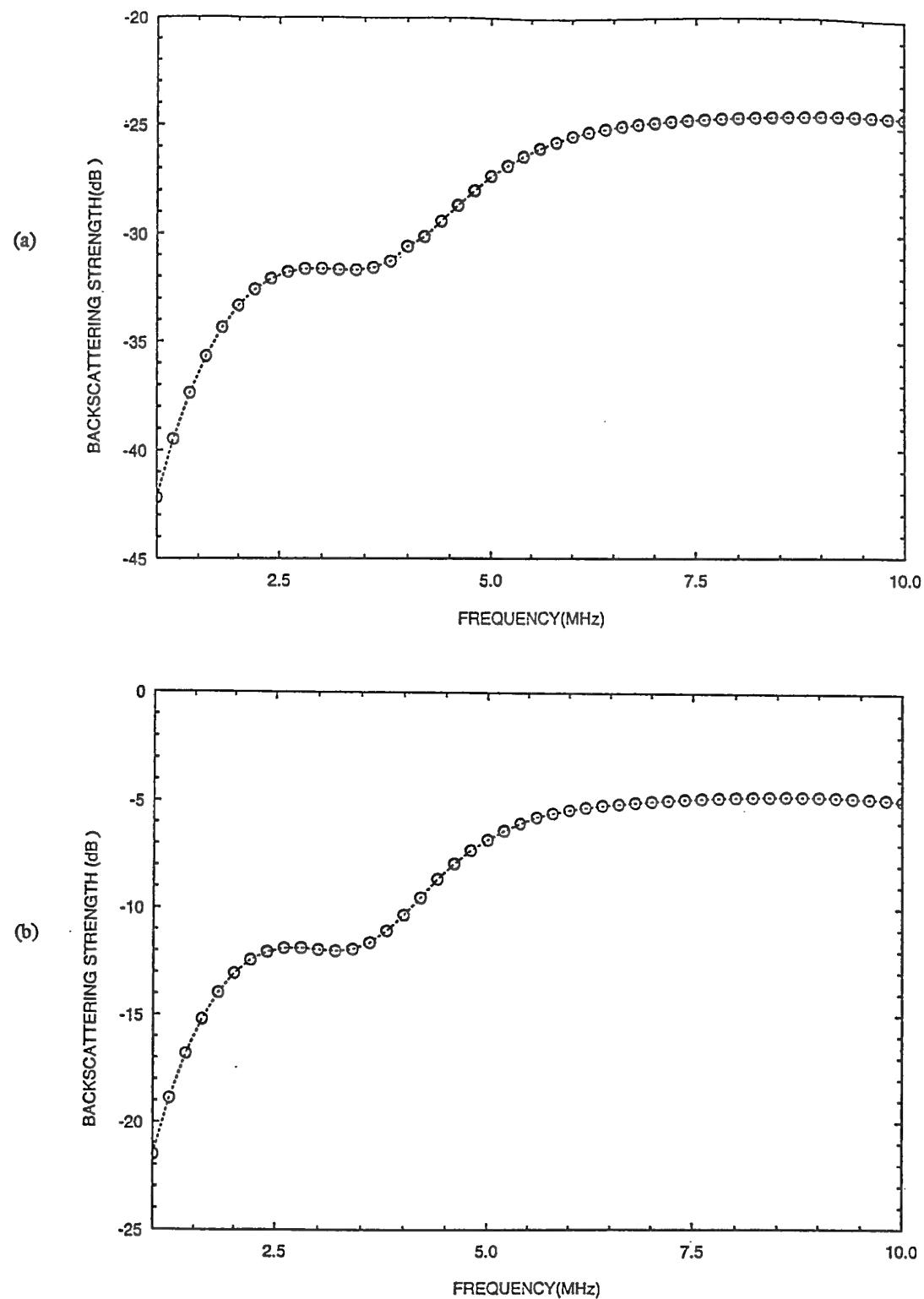


Figure 5: Backscattering strength at (a) 80 cm and (b) 10 cm from the bottom of an estuary for frequencies 1-10 MHz.

## 7. Conclusion

This paper provides theoretical estimates of attenuation and backscattering strengths due to suspended sand particles at frequencies in the 1-10 MHz region. Four different situations are examined. The first case involved the use of volume concentration of particles in the shallow layers (0-200 m) of the ocean. Results showed that thermal attenuation is negligible for all particle sizes ( $<10^{-3}$  dB/m at 5 MHz). For particles with radii less than 10  $\mu\text{m}$  viscous drag is the dominant cause of attenuation. For particles having radii near 1  $\mu\text{m}$  viscous attenuation is approximately  $10^{-1}$  dB/m at 5 MHz. It decreases with radius beyond 0.5  $\mu\text{m}$ . Attenuation due to scattering for particles having radii near 1  $\mu\text{m}$  is less than  $10^{-5}$  dB/m at 5 MHz. Attenuation due to scattering increases with radius and beyond 10  $\mu\text{m}$  it is the main contribution to attenuation. For particles near 50  $\mu\text{m}$  attenuation due to scattering is  $10^{-1}$  dB/m at 5 MHz while viscous attenuation is about  $10^{-3}$  dB/m. Backscattering strength increases with particle radius and varies from -80 dB to -25 dB as particle radius changes from 0.5 to 50  $\mu\text{m}$ .

The second case involved the use of the particle size distribution of McCave [1984], valid near the clear water minimum. This distribution is obtained from a large number of measurements in the North West Atlantic, Mediterranean and the East Pacific. For this distribution, in the 1-5 MHz region the total attenuation is mainly due to viscous drag and has a value of approximately  $10^{-4}$  dB/m. Beyond 5 MHz scattering too becomes important and the total attenuation is  $5 \times 10^{-4}$  dB/m. Viscous attenuation is fairly constant over 1-10 MHz frequency range, while attenuation due to scattering varies from approximately  $10^{-7}$  to  $10^{-4}$  dB/m over this frequency range. Backscattering strength increases with frequency and varies from nearly -80 to -50 dB over the frequency range 1 to 10 MHz.

The third case involved the measured particle size distribution near the Bay of Bengal in the Indian Ocean, at 10 m depth. The radii of all particles were less than 10  $\mu\text{m}$ . The attenuation is mainly due to viscous drag and has a near constant value of approximately  $4 \times 10^{-3}$  dB/m over the 1-10 MHz frequency range. Backscattering strength increases with frequency and shows a similar variation to that obtained for clear water.

The last case used suspended sediment measurements made in an estuary at two different levels 80 cm and 10 cm from the bottom. At both depths the main contribution of attenuation is from scattering, with viscous attenuation being negligible in comparison. This arises due to the presence of large particles present at these depths, the average radius being around 80  $\mu\text{m}$ . For particles with such radii viscous drag is small. At 80 cm from the bottom, attenuation varies from  $10^{-3}$  dB/m to about  $10^{-1}$  dB/m over the frequency range 1 to 5 MHz. In the 5-10 MHz region variation is small, attenuation being close to  $10^{-1}$  dB/m. At 10 cm from the bottom,

attenuation varies from  $10^{-1}$  dB/m to 10 dB/m over the frequency range 1 to 5 MHz, while in the 5-10 MHz region it is nearly constant around 10 dB/m. Backscattering strengths at 80 cm from the bottom varies from -42 dB to -25 dB over the frequency range 1-5 MHz, remaining fairly constant at close to -25 dB, in the 5-10 MHz range. At 10 cm above the bottom, backscattering strength varies from -22 dB to -5 dB in the 1-5 MHz region, remaining constant at around -5 dB in the 5-10 MHz range.

The study shows that the predominant mechanism for attenuation is viscous drag for particles with radii less than  $10 \mu m$ , while those with larger radii it is scattering. Although attenuation results in loss of acoustic energy, backscattering is of more serious concern. It can cause glitter in the screen and can mask the image of the object that is of interest. Large sand particles are mostly present close to the sea bottom and it is here that acoustic visibility would pose problems.

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Theoretical Estimates of High Frequency Acoustic Attenuation and Backscattering from Suspended Sand Particles in the Ocean and in an Estuary

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## ABSTRACT

Theoretical estimates of high frequency sound attenuation and backscattering strengths from suspended sand particles in the ocean and in an estuary are given. The estimates are obtained using the measured volume concentrations of suspended particle in the upper layers of the ocean [Duykers, 1967], from the particle size spectra near the clear water minimum [McCave, 1984], and from measurements of suspended sediments at different depths from the bottom of an estuary, [Thorne, et al, 1993]. Estimates are given for frequencies in the 1-10 MHz region. Contributions to acoustic attenuation from scattering, viscous drag and thermal conduction are evaluated separately using existing theoretical models. Contribution to attenuation from thermal conduction is negligible at the frequencies used. For particles in the sub micrometer to 10  $\mu\text{m}$  range attenuation is predominantly due to viscous drag. For large particles scattering is the main cause of attenuation. Estimates reveal attenuation and backscattering near the bottom of the estuary is quite high. At 5 MHz, attenuation at a depth of 80 cm and 10 cm from the bottom are approximately 0.1 dB/m and 10 dB/m respectively. At this frequency backscattering strength at 80 cm and 10 cm depths from the bottom, are approximately -25 dB and -5 dB respectively.

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